BEST3 CONFERENCE –077 Sloped Glazing – Problems and Solutions Karol Kazmierczak

Introduction.

The seminar presents typical challenges and solutions associated with sloped glazing and skylights. The seminar presents a history of development of sloped glazing, different classifications, including the one developed by the author on basis of the air barrier location, types of internal and external drainage of sloped glazing, structural challenges typical sources of failures, applicable construction testing procedures, code compliance, maintenance access to the sloped glazing, safety standards, challenges involved in obsolete code interpretation as related to the modern glazing, analyses of frequently misunderstood details, examples of correct details, and energy ramifications of sloped glazing. Case examples will include typical cases of leakage, condensation and icing, thermal simulations of skylight, as well as a structural collapse of a monumental sloped glazing. Many designers and builders treat sloped glazing as it were a tilted curtain wall. However, this proved to be one of the most challenging assemblies, seldom fully understood by their own manufacturers, fabricators, and installers, as well as building enclosure consultants. This may be well illustrated by the fact that rain water leakage of sloped glazing is as unique as it is widespread: it's unique among other leakage cases because the source and location of a leak may often be obvious; however, it still requires a thorough expertise to understand the mechanism and devise a fix. It's widespread because many glazings were designed and built wrong from the start, and botched glazings have often successfully resisted multiple investigations and repair attempts. This seminar focuses on areas typically overlooked by architects and engineers in process of building envelope design. The topics are chosen on basis of observations derived from both forensic investigations of failed assemblies and peer reviews of architectural documentation.

Sloped Glazing Historically

Figure 1 Oculus in Pantheon in Rome. 1st century.

Figure 2 Roof Lantern on Cathedral in Siena, Italy. 13th century.

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Early Developments

Oculus, placed at the apex of a dome, has been developed two thousands years ago, with the Pantheon in Rome (Figure 1) being a frequently cited example. It has not been covered by any glazing, giving it a parallel "rain-hole" name. In Renaissance, overhead day lighting of enclosed spaces has been accomplished by architectural lanterns, with glazing positioned vertically in a form of modern clerestories. They were followed by glazed roofs in orangeries and conservatories in the early 19th century, which can be considered the earliest examples of the sloped glazing in the form known today. These structures, used to grow citrus plants in colder climates capitalizing on the solar heat captured by glass, would be called greenhouses in modern times . These early assemblies were not expected to provide much water-tightness .

Figure 3 Condensate drainage in 1916 skylight in Cleveland Museum of Art, Cleveland, OH.

Figure 4 Operable internal louvers in 1916 skylight.

Figure 5 Movement joint with split rafter in the 1916 skylight.

One century ago.

Capitalizing on the industrial development of the 18th century, the sloped glazing has been based on wired or screened glass applications supported on rolled steel profiles. Weather seal and transfer of forces along glass edges was achieved by insertion of isolating compressible materials e.g. thin wood strips, clamped along rafters and purlins. Perpendicular glass edges were often soldered with lead. Flashing was sometimes soldered continuously along the glass edge. Supporting structure was divided by movement joints, with double rafters to allow for differential thermal movements. Some of these early applications survived till recently. A good example was the monumental skylight above the 1916 building of Cleveland Museum of Art in Cleveland, OH, dismantled only few years ago. The sloped glazing was equipped with separate internal condensate drainage system. This sloped glazing was also equipped with elaborate, remotely-operable internal shading devices, to protect the sensitive artifacts from fading. The sloped glazing was engineered and produced very well by modern standards. However, the shades have been found to be inoperable and the sloped glazing leaked water and air, dripped condensation, and exhibited icicles inside when inspected during winter six years ago.

Half a century ago

Introduction of aluminum extrusions and durable elastomeric rubbers boosted the sloped glazing with mass-production capabilities for typical applications. Both the glass attachment and weather seal became easier to produce and offered better performance. Introduction of laminated and organic glass liberated sloped glazing from wires and nets. These applications are still fairly common today. A good example is the set of pyramid skylights built in different decades of the second half of the 20th century, examined in Louisiana in 2007 (Figure 6). They have been investigated and found to have been remedially sealed several times during their life; however we found them still leaking profusely, mainly due to their inadequate engineering. Applications from this era were also sometimes characterized by lack or incomplete thermal solutions, resulting in miscellaneous failures, ranging from dripping condensation to a serious structural collapse caused by installation of insulated glass on a framing system not adapted to transfer the additional dead load. The spectrally selective glass have been gradually developed, with the tinted glass and external pyrolytic coatings as early attempt examples.

Figure 6 One of typical pyramid-shaped skylights built from 1950's in Gretna, LA.

Figure 7 Sloped glazing on a latticework in Jacob K. Javits Convention Center r in New York City in 1980's.

Recent decades.

Modern sloped glazing benefited from the accelerated development of glazing materials experience in the latest decades. Large size, laminated glass and insulated glass with protected, sputtered low-E coatings became the standard, sometimes supported on laminated glass beams and tensegrity structures for increased transparency. Double curvatures and

Figure 8 Modern sloped glazing on double curvatures.

structural shells were designed (Figure 8). Operable fields have been developed to be more reliable, and the retractable sloped glazing came mainstream, allowing for efficient ventilation. More durable and reliable weather sealants have been developed. However, the average user still complains about the dripping water, the most widespread failure of these assemblies.

Figure 10 Sloped glazing built in 1980's investigated after collapse. 2008

Performance

Dripping water, either resulting from an inadequately addressed condensation or rain water intrusion, is the prevalent mode of failure for the sloped glazing, regardless of age. It in turn leads to either slippery conditions becoming a fall hazard or the damage of water-sensitive materials. The original name "rain-hole" has not lost its significance. The sloped glazing is one of these rare assemblies, in which the source of leak may be self-evident, yet there is a long way to diagnosis of the problem. Other failures include collapse, glass blemishes, inborn noise, thermal discomfort, glare and maladjusted day lighting.

Figure 11 Sloped glazing in lieu of roofs.

New challenges

The architectural Deconstructivism merged curtain walls with sloped glazing and substituted roofs with sloped glazing, as illustrated by numerous recent building examples (Figure 11). Large skylight-roof area ratios drain energy for air conditioning, and subject conversely larger spaces to the above-mentioned elevated functional failures' risk.

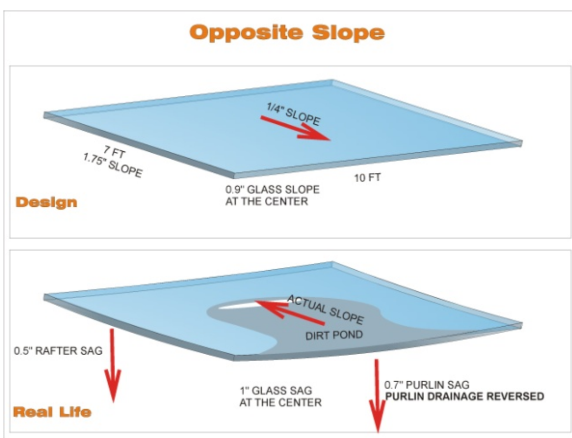


Figure 12 Coordination of slope with deflections. At eaves, the bottom purlin is often stiffer than the upper one causing water ponding.

Codes and Definitions

Lecture of International Building Code brings two contradictory definitions of skylights: either 30 or 15 degrees from plumb. Reverse-tilt applications are considered skylights. Some codes have not yet caught

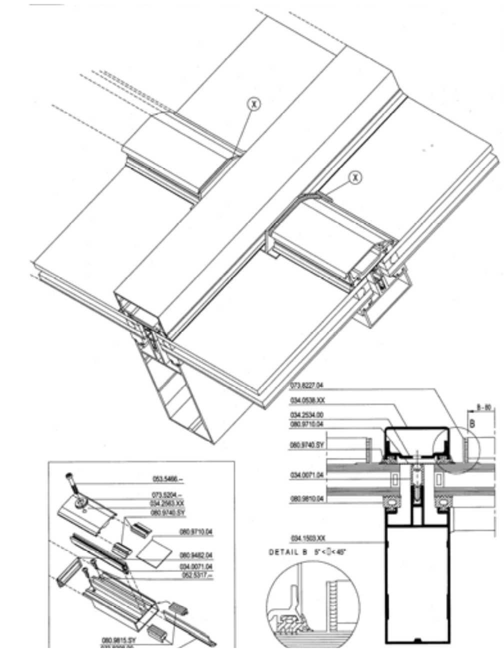


Figure 13 Good engineering. Drainage by gaps left at tapered purlin caps. European catalog.

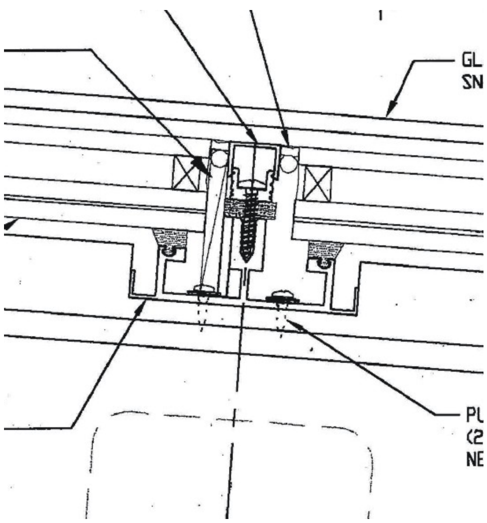


Figure 14 Suppression of the purlin cap in the extrusion system not-adapted for the structural seal and large glass size. Even if the glass edges were not left unsupported, the aluminum extrusion has insufficient stiffness to support the glass. Exterior weather seals are not continuous. The condensate drainage system breaks the air barrier in spite of the dedicated separate gutter on the rafter. Built in Salt Lake City, UT, 2009.

up with the introduction of laminated glass some 70 years ago, and require archaic screens and wired glass. Industry associations, such as AAMA came with standards addressing the most typical units used in small and middle-size construction.

AAMA (American Architectural Manufacturers Association) and WDMA (Window and Door Manufacturers Association) give the following definition of the sloped glazing, in the 101 standard titled "Voluntary Performance Specification for Windows, Skylights and Glass Doors:"

> SLOPED GLAZING (other than SKYLIGHTS): A glass and framing assembly that is sloped more than 15° from the vertical and which forms essentially the entire roof of the structure. Generally this is a single slope construction.

This naturally brings the question about the definition of skylight, also defined in the same standard:

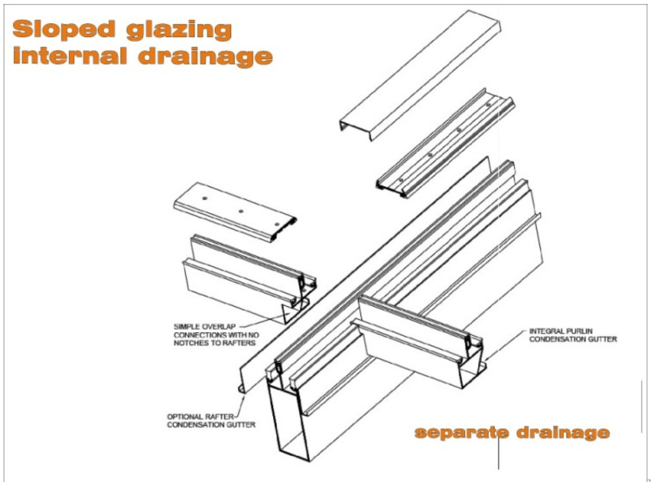
> SKYLIGHT: sloped or horizontal application of a fenestration product in an out-of-reach application, which allows for natural daylighting. Skylights shall be either fixed (non-operable) or venting (operating). Unlike roof windows, skylights need not provide provisions for cleaning of exterior surfaces from the interior of the building.

Three Drainage Layers

The average sloped glazing typically needs three levels of water drainage: external, internal, and condensate collection, described below:

External Drainage

The external drainage is accomplished by sloping the glazing to allow for evacuation of water from its exterior surface. The slope ratio should overcome the combined framing and glass deflection (Figure 12) and the purlin



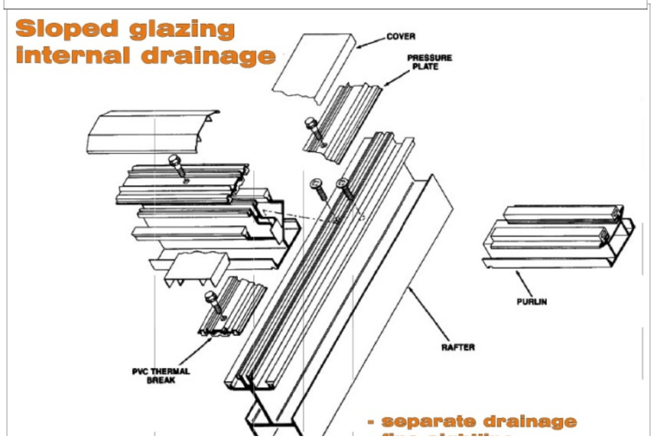


Figure 15 Separate condensate drainage systems maintain the integrity of the air barrier but discharge at a lower point. American catalog.

design should allow for evacuation of water at a sufficient rate of speed to prevent sediments. This should be normally accomplished by a gap left at purlin caps (Figure 13) or flat or tapered shape of purlin caps. Unfortunately, this solution is not popular in America; therefore, architects opt for the elimination of the purlin cap, causing overflowing of the interior drainage system. Figure 14 shows a copy of a shop drawing illustrating such an attempt. In this case, not only the weather seals are challenging to produce according to the manufacturer's requirements, but also they are interrupted below every rafter cap. The designed purlin profile is not suitable for this application because it lacks the sufficient substrate for structural seal beads, which should hold the glass edges at the absence of the gasket compression offered by the suppressed purlin cap. It's also too shallow a profile to limit deflections to avoid water backflow.

Interior Drainage System

This system is composed of internal channels collecting and discharging the accidental moisture. This is accomplished by the extrusion design resembling curtain walls, but the similarities end here. Pressure equalization of this system is typically accomplished by protected openings at the bottom and the top of the system only, to avoid exposing the system to bulk water. In systems popular in America, the primary seal developed in the back of this drainage system is often poorly detailed, penetrated by bolts, with purlin connections fixed by screws penetrating to the dry zone, without adequate seals, and with rafter expansion joints above dead load anchors sealed with sealant, stressing three sides of the glazing seal. In some systems the excessive purlin deflections cause backflow, and the rafter terminations at eaves sometimes discharge water toward the interior.

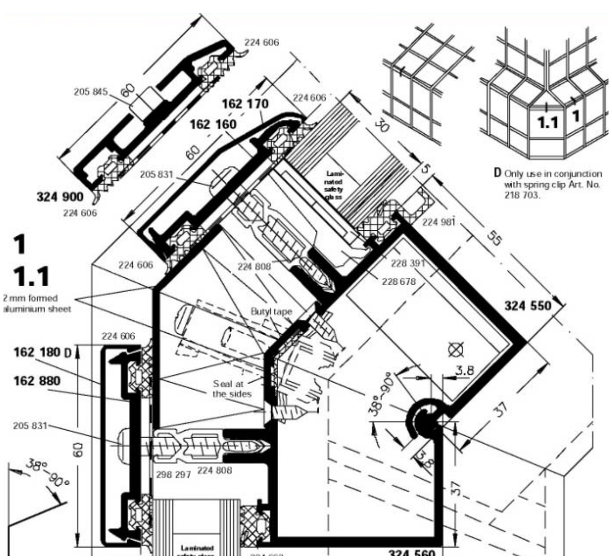


Figure 16 Integrated system allows for easier discharge but penetrates the air barrier at every purlin. European catalog.

Condensate Drainage Systems

Majority of skylights develop condensation on the interior glass surfaces daily. Such condensation may be deemed undesired if it can damage water-sensitive materials, cause slip-hazards, stain adjacent surfaces, drip into someone's meal, or otherwise conflict with the intended function of the space. If the glass is sloped sufficiently to allow water droplets roll on its surface, than a gutter located on the upper side of a purlin is able to collect this water. If the purlin is sized sufficiently to maintain its shape, and the ends of the gutter are sealed in a way allowing for differential thermal movements, the condensate would drain into the gutters placed at the rafters. It can be accomplished in two ways: <u>an integrated system</u> (Figure 16) with the described-above interior drainage used for condensate discharge at rafters, or <u>a separate system</u> (Figure 15) with dedicated gutters along rafter sides. The benefits of the integrated system are the easier discharge at eave (at a higher point) and slimmer sightlines of rafters. The main drawback is penetration the air barrier at every purlin; such a glazing system leaks air and water at a higher rate than a separated system, which maintains the integrity of the air barrier. Some systems seen in America combine the disadvantages of the two, as seen in the Figure 14. The system presented here not only unnecessarily penetrates the main air barrier, but also widens the rafter optically by having unused side rafter gutters. Others combine the advantages and e.g. manage to keep the drainage separate and maintain the slim sightline, as shown in the lower example at Figure 15. One of the most common design errors is lack of external discharge at eaves and sills (Figure 18). The eave design should address the condensate discharge as illustrated on an integrated system seen in Figure 17.

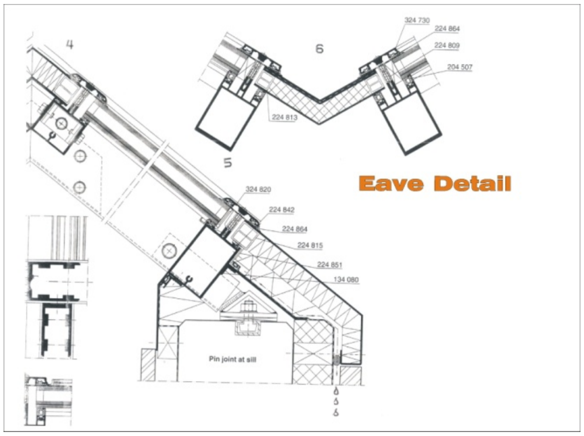


Figure 17 A rare, correctly designed eave detail of condensate discharge seen in European catalog. Integrated system.

Figure 18 Popular (bad) example of the eave discharge below the sill flashing and roofing, causing the leak in the food court below. West Palm Beach, FL.

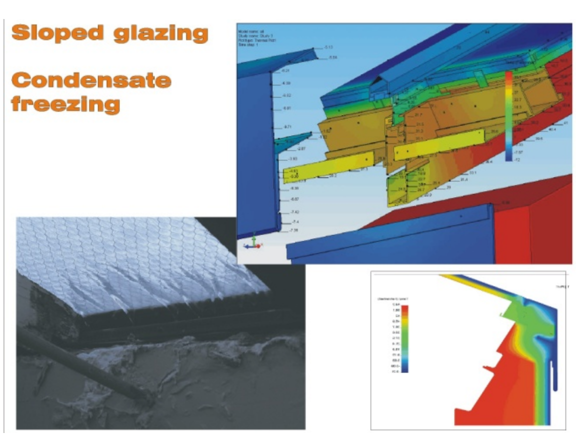


Figure 19 Three-dimensional thermal analysis confirmed the freezing risk of drainage paths. Cleveland, OH.

Figure 20 Collapse of the sloped glazing due to thrust inadequately resisted by anchor points.

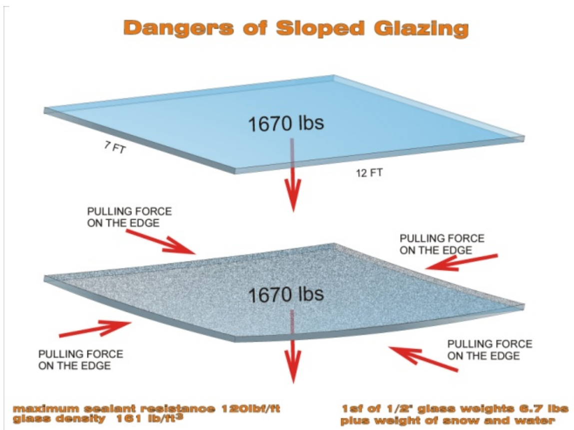


Figure 21 Modern large size of glass present unique structural challenges.

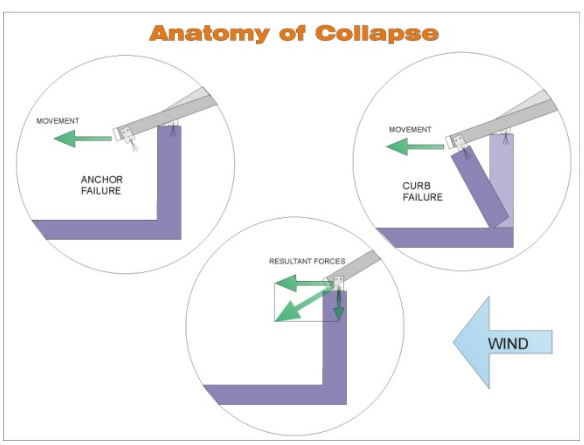


Figure 22 Collapse of the sloped glazing due to thrust not resisted by anchor points.

Heat Transfer

Thermal transmittance is affected by orientation, in spite of only 31% of architects believing it (according to the results of "Elementary Scientific Literacy Quiz for Architects" survey conducted by BEC Miami). E.g. A piece of glass bearing a NFRC label showing U value 0.24 would loose 46% the very moment it's tilted, diminishing its U value to only 0.35. This is why building codes require a conversely higher heat resistance of sloped assemblies and also limit skylight-to-roof ratio to 3% or 5%. Misunderstanding ot the thermal resistance may result in a last-minute substitution of a single glazing with insulated double glazing. Such a substitution increases the dead load approximately 50%. Placing an insulated glazing on a system not adapted to the additional load may result in a spectacular collapse (Figures 10 and 20). Furthermore, placing such a system on a secondary curb structure not adapted to resist the associated thrust would result in overturning it (Figure 22).

Another frequent issue is the lack of thermal insulation at perimeter flashings and transitions, resulting in failures, such as the water drainage systems freezing in a winter and discharging water toward the interior. Such a risk should be assessed by three-dimensional thermal computer simulations or testing (Figure 19).

Structural Resistance

Sloped applications are characterized by lower entropy than vertical, therefore, require a more careful approach to the secondary structure and users' safety. Sloped application come in

Figure 23 Exterior glass floor is considered a skylight.

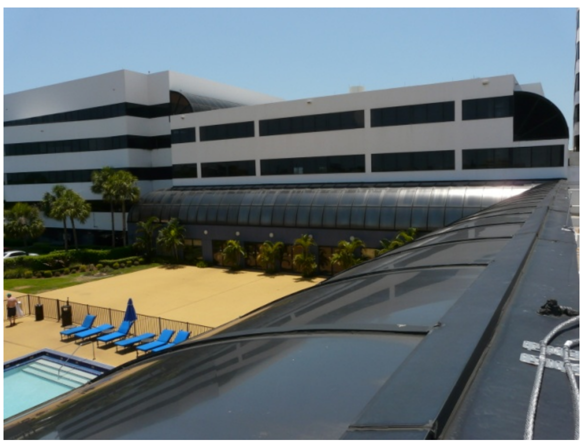


Figure 24 Long stretches of sloped glazing require multiple movement joints to accommodate the differential movements.

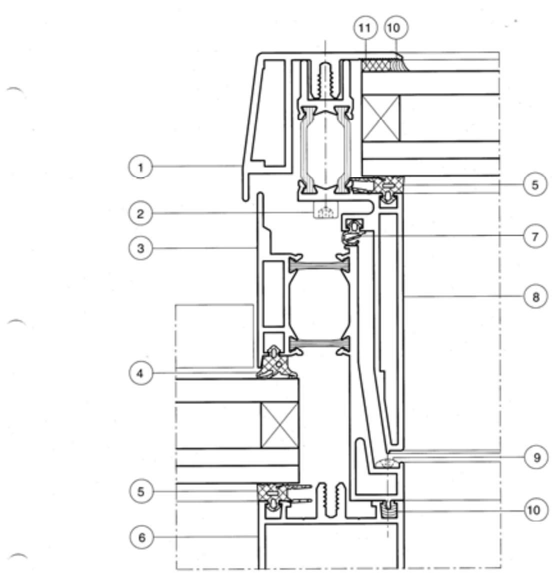


Figure 25 Proprietary design of a slim-sightline operable panel.

many support varieties, which can be roughly divided into two categories: imposing thrust on its support points or not. The most interesting are shells, with glass panes contributing to the load resistance, saving the secondary support and increasing the overall transparency. In double-curved applications, much design effort is exerted to limit the individual glass curvature to allow for flat or cold-bent panes. Triangular glass panes may require double-level drainage systems. Glass is not considered a walking surface; therefore, unless a gantry is designed, the maintenance may require expensive portable cranes and aerial platforms, which should be able to access the adjacent spaces. The code extends the definition of skylights onto overhead glazing; therefore, embracing the glazed exterior floors (Figure 23). Large glass sizes used nowadays may overstrain the perimeter attachment in the unlikely event all glass layers are broken (e.g. discharge of a firearm) due to the significant weight which may be combined with live loads, such as snow and water (Figure 21). The thermal inefficiency inherent in sloped glazing makes snow and ice management challenging. Many applications require netting to protect the upper surface against small impact. Examples include security and penitentiary applications, as well as sloped glazing of e.g. hotel lobby located below balconies, from which guests are known to throw bottles. Differential shading should be analysed to verify the glass thermal overstress risk.

Movements

Aluminum and steel are characterized by thermal expansion coefficients larger than concrete and glass. Therefore, a large sloped glazing should be divided by movement joints, which typically require double rafters. Also, every connection should allow for the associated differential thermal movement. Lack of movement joints can be heard as a cracking noise. The most typical source of failure is the design of seals in a way that would be compromised by the movements.

Operable panels

Sloped glazing may require placing remotely-operable panels for e.g. heat or smoke exhaust. They are designed as typical roof windows curbed into the glazing pockets. Some sophisticated solutions allow for slimmer sightlines (figure 25) or elimination of the curb (Figure 26). Some models of sloped glazing is designed as entirely retractable, allowing for the full air exchange.

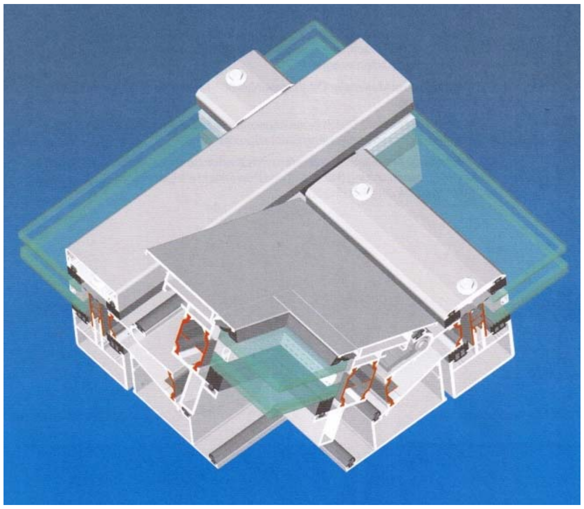


Figure 26 Proprietary design of a flat operable panel.

Figure 27 Collection of dirt. Berlin, 2008

Dirt Management

Valleys, gutters, and insufficient slope contribute to the sedimentation associated with insufficient air and water velocity for particle removal at the surface (Figure 27). The modern hydrophilic "self cleaning" glass is often specified as a remedy. However, such a glass type needs a sufficient slope to allow for rain washing.

Figure 28 Corrosion and exterior condensation on pyrolytic coating. West Palm beach, FL 2011.

Day lighting and Solar Energy

The overhead glazing is the best source of daylight. However, excessive size may result in significant solar heat gain, resulting in thermal discomfort and large energy bills. The most typical shading systems consist of interior fabric shades, stretched in a form of a tent below the glazing. The overhead glazing is typically coated with spectrally-selective and reflective coatings (Figure 28). The glass is also tinted in mass, laminated with tinted interlayer, and coated with opaque ceramic coating patterns to permanently reduce the transmission. A thin-layer photovoltaic coating can be applied to achieve a similar effect and harvest the solar energy.

Summary

Sloped glazing combines challenges of a roof and a curtain wall. Both are seldom understood by designers resulting in the perception of the sloped glazing being often considered the faultiest part of a building envelope. We discussed several typical aspects of performance, focusing on the most overlooked solutions..

Sources.

In addition to the author's materials, the following sources were used:

- Aluminum Manufacturers'Catalogs: Schueco, Reynayers, Kawneer, Hueck.

- Figure 1: Wikipedia.

- Figure 2: Marzena and Jacek Bruzdowicz 2011

- Figure 23: Detail Magazine, issue 10/2004.